Inter-annual Variability and Prediction of Eddies in the Gulf of Aden and the Somali Current Region

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Grant Number: N000140710958
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LONG-TERM GOALS

It is the research goal to understand and quantify the physical processes that determine the air-sea interaction, currents and hydrography in the western Indian Ocean and Arabian Sea, from diurnal time scales to inter-annual variability.

OBJECTIVES

The objective of the proposed research is to provide a detailed investigation of the physical aspects of eddies found in the Gulf of Aden and in the Somali Current region in the Arabian Sea. The project will quantify the physical characteristics and statistics of the eddies, including their horizontal scales, their strenght with depth, their influence on temperature, salinity and density, their generation and their life span.

More specifically, the objectives are

To provide a climatology and statistics of eddy fields in the Gulf of Aden based on observations from satellite altimeters and hindcast ocean models and to obtain a comprehensive understanding of the eddy generation and dynamics.

To investigate the impact of the eddies on air-sea interaction using correlation analysis between sea surface height anomalies and air-sea fluxes.

To determine the predictability of eddy fields from observations and numerical models.

APPROACH

The questions above will be addressed relying primarily on two key sources of information. We proposed to analyze sea surface height from combined TOPEX/Poseidon, ERS and Jason altimeter data set and the output from state-of-the-art models to investigate the inter-annual variability of Gulf of Aden eddies and the mechanisms that generate them. SSH from T/P altimeter is the best source for high-resolution observations of the eddy fields. OGCM runs can be used for a detailed 3-D analysis of eddy dynamics and their impact on SST, upwelling and vertical density structure. Output with a 3-day

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE	
Inter-Annual Variability And Prediction Of Eddies In The Gulf Of Aden And The Somali Current Region	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Hawaii at Manoa,International Pacific Research Center,1680 East-West Road, POST Bldg 401,Honolulu,HI,96822**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
It is the research goal to understand and quantify the physical processes that determine the air-sea interaction, currents and hydrography in the western Indian Ocean and Arabian Sea, from diurnal time scales to inter-annual variability.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

frequency is available from the Ocean model For the Earth Simulator (OFES) hindcast run forced with NCEP re-analysis (1950 – 2005). This data is already available at the International Pacific Research Center (IPRC) at University of Hawaii. Nowcast/forecast runs from the Naval Research Laboratory using HYCOM is available for selected periods from Jan 2003 until present from COAPS, FSU and will be included at a later stage of the project.

These data sources will be supplemented using observational data sets (Table 1 below) to determine an impact of eddies on air-sea interaction. In particular, it is anticipated that negative SST anomalies associated with cyclonic eddy activity may suppress mixing in the planetary boundary layer and weakening the surface wind as a result. Conversely, the relatively higher SST in anti-cyclonic eddies tend to increase the depth of the planetary boundary layer and locally increase the near surface wind speeds and the latent heat flux. AVHRR SST and QuickScat winds will be used for this analysis.

For additional analysis and for evaluation of eddy predictability model output from eddy resolving layer models (NLOM) from the Naval Research Laboratory at Stennis Space Center will be used. The NRL NLOM have routinely been run in nowcast mode and forecast mode after assimilation of data and the output is available for analysis at the IPRC. Details are given in Table 2 below.

Observational Data Sets

Most available observational data sets are too limited in spatial and temporal resolution to adequately resolve eddies along the Arabian Peninsula. This is in particular true for air-sea heat flux data sets. The following data sets will be used for analysis:

TABLE 1

Observed Data set	Resolution	Time span	Variables
TOPEX/Poseidon/ERS/Jason1 combined altimeter data	0.25^{o}, weekly	10/92 - 6/03	SSHA
AVHRR Pathfinder v.5	4 km, daily	1985-2004	SST
WHOI OA heatflux	1.0^{o}, daily	1/81 -12/02	LH, SH
ISCCP	1.0^{o}, daily	1/81 -12/02	Net SW, net LW
Quickscat	0.25^{o}, 3 day	7/99-01/06	TX,TY
SeaWIFS	0.25^{o}, weekly	10/97-11/05	chlorophyll

These data sets have relatively high spatial and temporal resolution necessary to resolve the eddies. An exception is the ISCCP radiation data. This data has been interpolated to the same grid as the WHOI objectively analyzed heat flux data from a resolution of 2.5^{o}. The latter data sets as well as Quickscat will be used to investigate possible air-sea interaction over eddies. The SeaWIFS data will only be used to help identify upwelling regions.

Monthly eddy climatology and inter-annual variability

The eddies drift westward along the Arabian coast so it is useful first to establish maps that show their monthly positions. Preliminary examination of high resolution model output from inter-annual runs indicates that several eddies appear in the same locations each year although year to year variability

can be large. Therefore a monthly climatology will be established and year-to-year variations and climate extremes will be studied.

The manifestation of eddies is most significant in sea surface elevation so the first step is to produce maps of sea surface heights. Observed sea level heights will be computed from a combined weekly sea surface height anomaly (SSHA) from TOPEX Poseidon, ERS and Jason1 satellites. This data is mapped on a global irregular grid with $1/3^o$ spacing on average. Data is available from October 1992 through December 2003. There is variability from year to year so maps of monthly variance will also be produced.

From the observed SSH fields the barotropic part of the geostrophic currents will be computed and compared with model results from OFES and HYCOM.

Other observed quantities with high resolution are difficult to obtain, in particular sub-surface quantities, so the project will rely on model simulations for variables other than SSH and SST. The following model data sets will be used:

Model	Resolution	Time of data	*Variables*
OFES 50yr run Climatology forcing	0.1^o , 54 levels	Last 8 years Daily output	*SSH, u,v,w,T,S (3d)*
OFES hindcast	0.1^o , 54 levels	Jan 1950 - Dec 2004 Monthly	*SSH, SST*
HYCOM nowcast	$1/12^o$, 32 layers	Apr 2007 - present	*SSH,u,v,T,S (3d)*
HYCOM hindcast	$1/12^o$, 32 layers	Nov 2003-Dec 2004	*SSH,u,v,T,S (3d)*
HYCOM simulation	$1/12^o$, 32 layers	Jan 2003-Dec 2005	*SSH,u,v,T,S (3d)*
NLOM nowcast	$1/32^o$, 6 layers	Apr 28, 2005 - now	*SSH, SST, u,v at surface*
NLOM nowcast	*$1/16^o$, 6 layers*	*Jun 2002 -Mar 2006*	*SSH, SST, u,v at surface*

The Ocean Model for the Earth simulator is a full Ocean General Circulation Model and output from this model will be analyzed in most detail. The main advantage of the NRL NLOM model output is the higher horizontal resolution which may give different eddy characteristics and statistics than OFES or T/P SSH. In that case there is a possibility that the resolution of the observed SSH is inadequate.

Eddy Characteristics

The eddy scales will be determined from the data and models above. This includes eddy diameter, current speed, propagation speed and variation with depth.
The associated changes in temperature, salinity and density will be computed for a large number of eddies. Correlation of eddy scales between observations (SSH and derived barotropic geostrophic velocities) and model variables will be computed.

Generation mechanisms

The main hypothesis is that the eddies along the southern shore of the Arabian Peninsula primarily are generated by remotely forced Rossby waves. Along the west coast of India the wind generates upwelling and downwelling patterns, which result in Rossby wave radiation across the Arabian Sea (Jensen, 1991). This Rossby wave radiation was later confirmed by SSH observations from Topex/Poseidon (Brandt et al, 2002). A competing mechanism during the southwest monsoon is an extension of the Somali Current through the gap between the island of Socotra and the Horn of Africa which may drive eddy flow in the entrance to the Gulf of Aden.

Prediction

The remote forcing leads to a potential for forecasting the eddy field. It is proposed to produce correlation maps between SSH anomalies for a number of locations near 65^{o}E with latitudes ranging from 10^{o}N to 22^{o}N using the T/P-ERS data set. The same calculation will be computed for the OFES and NRL models. A comparison between the NRL nowcast model and the NRL forecast model output will reveal if successful forecasting of eddies can be done with an operational model.

WORK COMPLETED

In this section, representative results are shown which should give an overview of the state of the project and what type of data and analysis products has been produced to date.

Climatologies

The project started in August 2007. A monthly climatology of SSH anomaly relative to the 1993-2003 mean has been completed for the Topex/Poseidon/Jason composite product. Figure 1 shows the results during the transition from southwest monsoon regime in July through December where the atmospheric conditions are characterized by the northeast monsoon. This represents a time where numerous eddies and rings are formed in the western Arabian Sea.

Monthly SSH climatologies from two runs with OFES were also completed. One is forced by a monthly NCEP/NCAR reanalysis climatology (e.g. Kalnay et al., 1996) based on the years 1950 to 1999 and spun up for 50 years. The SSH anomaly climatology is computed using the last 6 years of this spin-up run. Details of the model and the forcing are given by Matsumoto et al (2004). The second model run is a hindcast of OFES (Sasaki et al., 2007) using the first run as initialization. This model is forced by daily NCEP/NCAR reanalysis fluxes from 1950 to 2006, and the SSH analysis cover the same period as the TOPEX/Poseidon data. Figure 2 shows the results from the analysis from July through December, and is directly comparable to Figure 1. In addition of a monthly climatology of SSH, month geostrophic current climatologies were computes from T/P data and for the model runs.

From Figures 1 and 2 it is seen that the overall structure of the Somali Current is very similar: The dominant feature is the Great Whirl until November, and to the north-east, a high SSH anomaly, the so-called Arabian Sea Dome (ASD) exists. Between this dome and the Great Whirl, low sea levels are associated with the cold upwelling region. Beginning in October, a large scale Rossby wave propagates in from the east and replaces the ASD with a low SSH anomaly. These large scale features are captured well by the OFES simulation. However, there are important differences: The Great Whirl

reaches its peak in July in the altimetry observations, but not until September in the model. Further, the commonly observed northward migration of the Great Whirl is seen in the satellite data, but not in the model.

In the Gulf of Aden, eddies in OFES are somewhat weaker than observed, but the positions of high and low SSH associated with the eddies are quite good. October is the month with most discrepancy. In OFES, the Great Whirl is too far to the south, and the SSHA is about 0.02 m too high near the equatorial region.

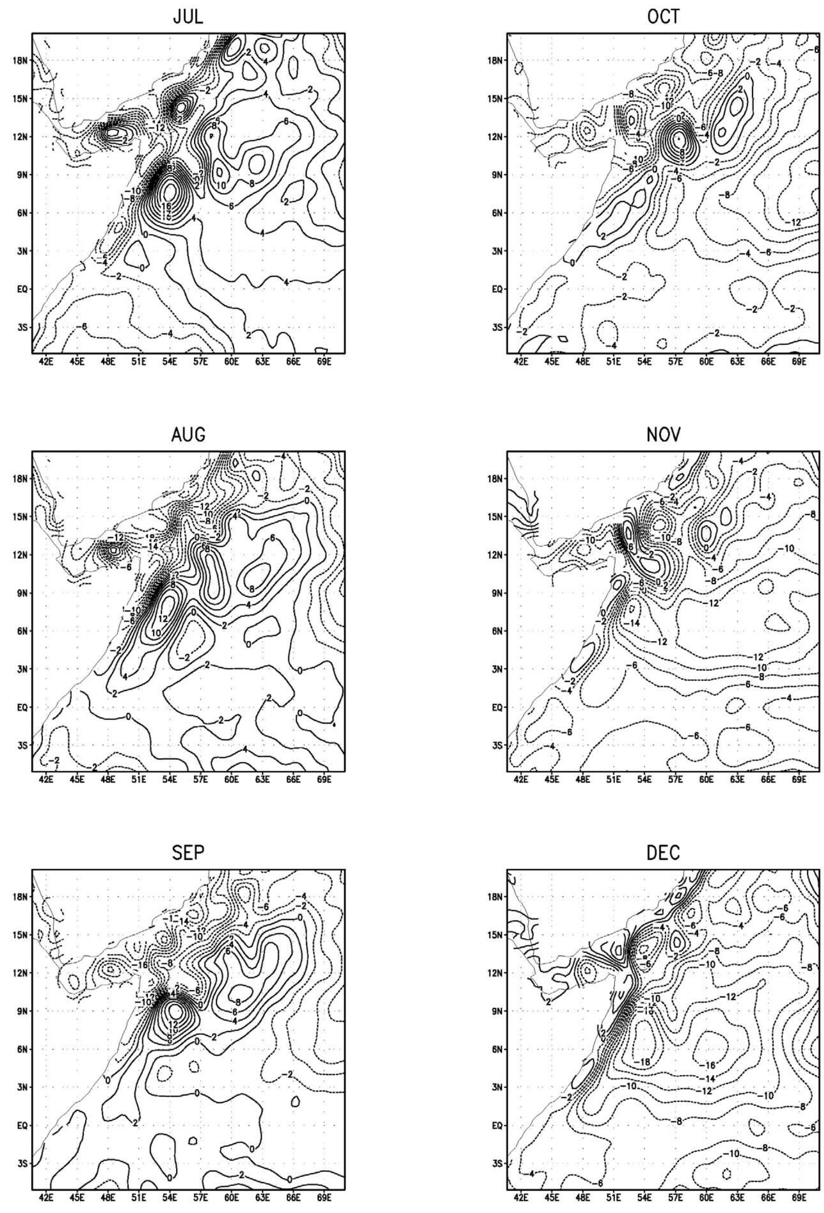

Figure 1. Monthly Sea Surface Height Anomalies computed relative to the 7 year mean from 1993-2003 from TOPEX/Poseidon-ERS-Jason altimetry.

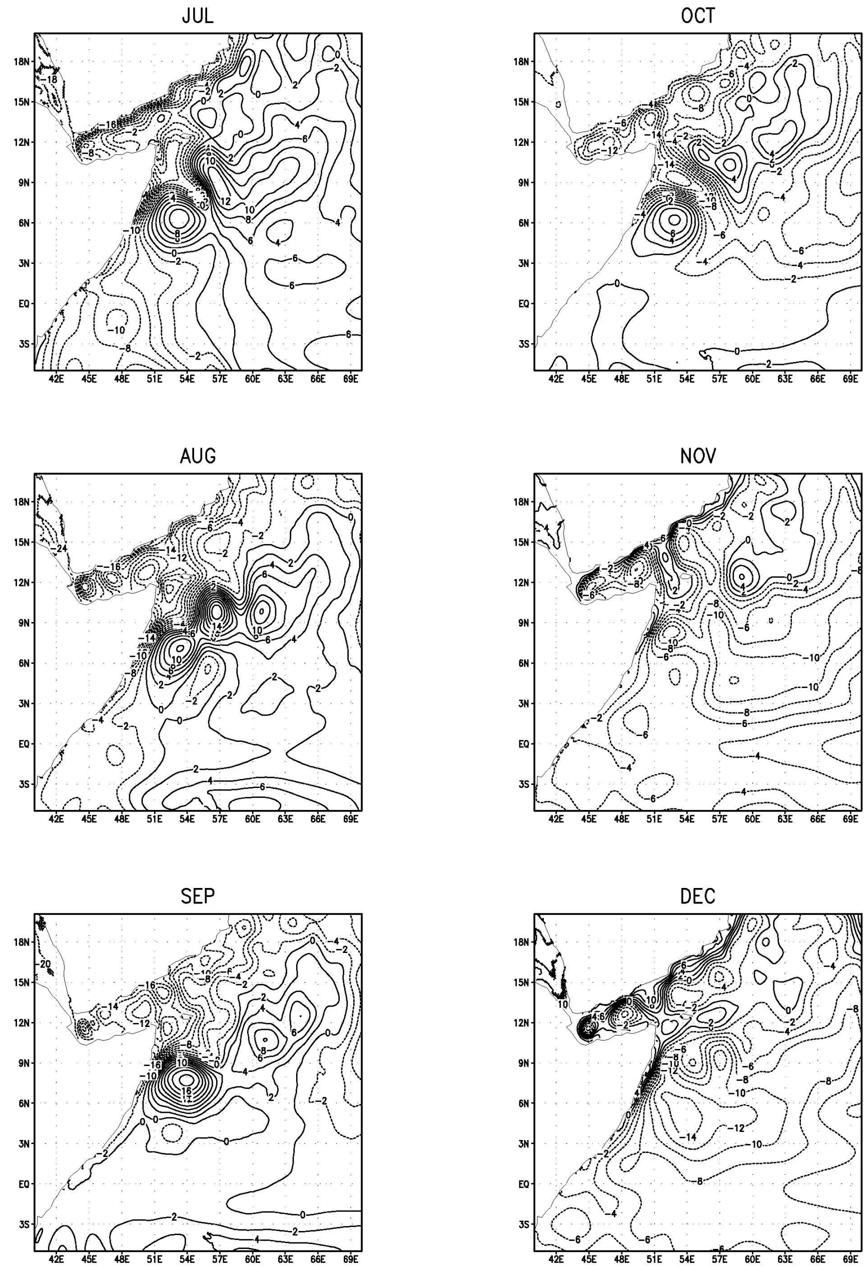

Figure 2. Monthly Sea Surface Height Anomalies computed relative to the 7 year mean from 1993-2003 from the OFES simulation

Inter-annual variability

The OFES model hindcast run is generally in good agreement with TOPEX/Poseidon climatology and is superior to OFES results from the spin-up run with climatological forcing. This implies that inter-annual variations in the forcing and/or high-frequency forcing have a significant impact on the mean circulation. Monthly SSH anomalies from OFES and TOPEX/Poseidon were computed from January 1993 to December 2003 and compared in the Somali Current region. The SSH from satellite observations as well as the model exhibits large inter-annual variations, but agreement is very good for

large scale features. The number of cyclonic and anti-cyclonic eddies are typically the same in model and observations, but the size and positions usually somewhat different. However, there is very good agreement on the seasonal change in eddy activity, e.g. most eddy activity from October through April in the Gulf of Aden. Similar agreement is seen for inter-annual variability of the strength of the Great Whirl off the Somali Coast. For instance, typically there are 2 cyclonic eddies and 3 anti-cyclonic eddies in the Gulf of Aden (see Fig. 3), although the flow in the Somali Current region has large inter-annual differences.

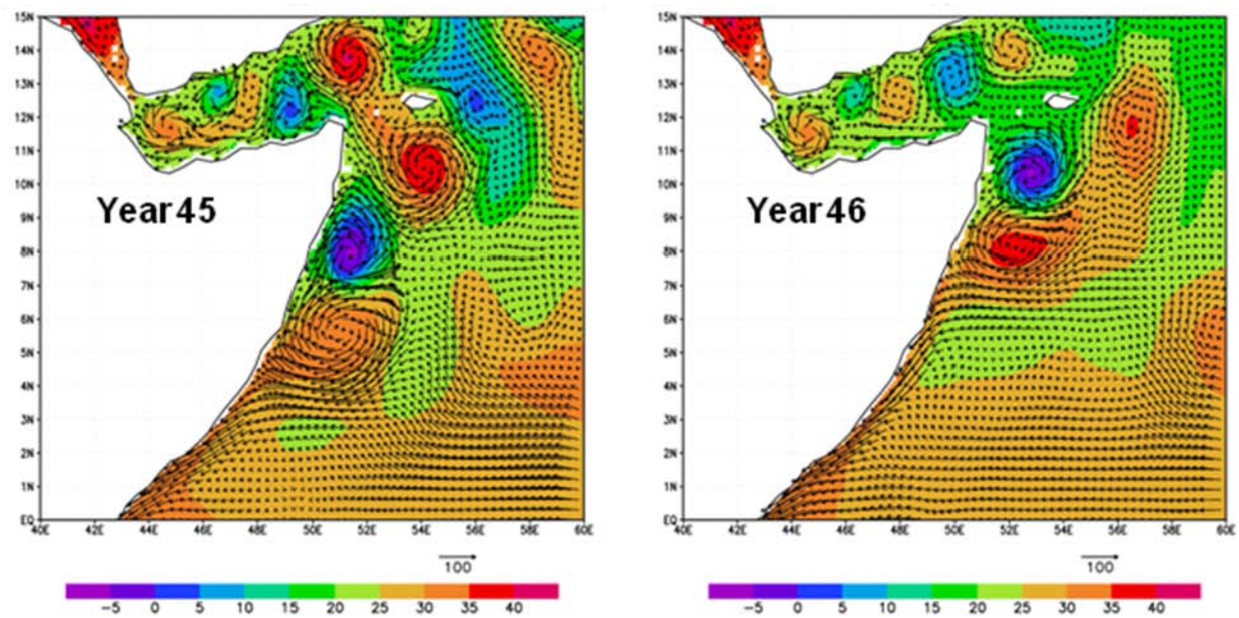

Figure 3. Sea Surface Height and surface currents for January from the OFES climatological run. Year 45 of the run (left) and year 46 (right). Note that the same type and number of eddies and their approximate position is the same in the Gulf of Aden, but large differences between the year-to-year flow in the Somali Current region exist. This is due to internal variability of the flows rather than due to forcing, which is periodic.

A closer comparison of the variations between TOPEX/Poseidon altimeter data and surface elevation anomalies (SSHA) from OFES has been done for the Somali Current region for the SSH climatology and for individual years. Eddy statistics, eddy potential energy (EPE), and spectral characteristics are compared over the area from the equator to 18^{o}N between 40^{o}E – 60^{o}E (Fig 4.).

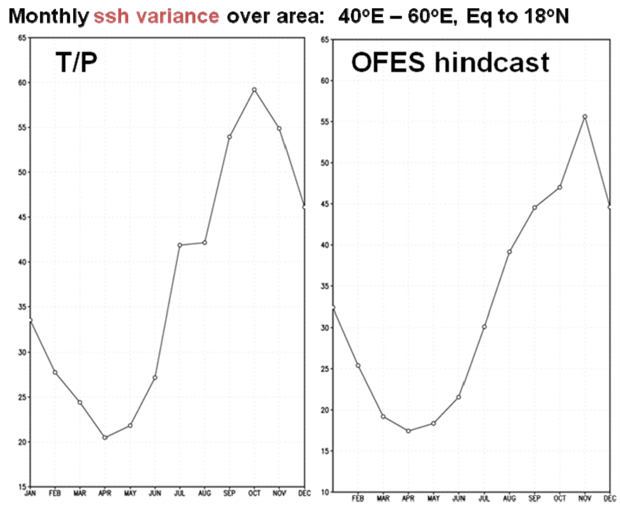

Figure 4. Monthly climatology of total variance of SSH between the equator and 18°N and from 40°E to 60°E from Topex/Poseidon (left) and the OFES hindcast run (right).

One important shortcoming in the OFES simulation is that the Great Whirl fails to move northward during the late phase of the summer monsoon, which is observed in many years, and the Great Whirl fails to break down until November or December in most years, about 1-2 month later than observed.

La Nina, El Nino and Indian Ocean Dipole years

Significant differences are found in the overall circulation of the northern Indian circulation in anomalous years, in particular during Indian Ocean Dipole events (e.g. Jensen, 2007). The on average clockwise circulation in the Indian Ocean reaches from the South Equatorial Current near 25°S to the Asian continent and encompasses the entire width of the basin. During an Indian Ocean Dipole year and to a lesser extent during El Nino, this circulation is intensified and is slowed down during a La Nina year. This variability is reflected in SSH variations in the Arabian Sea. Figure 5 shows that OFES can capture extremes anomalies in sea level on this inter-annual time scale.

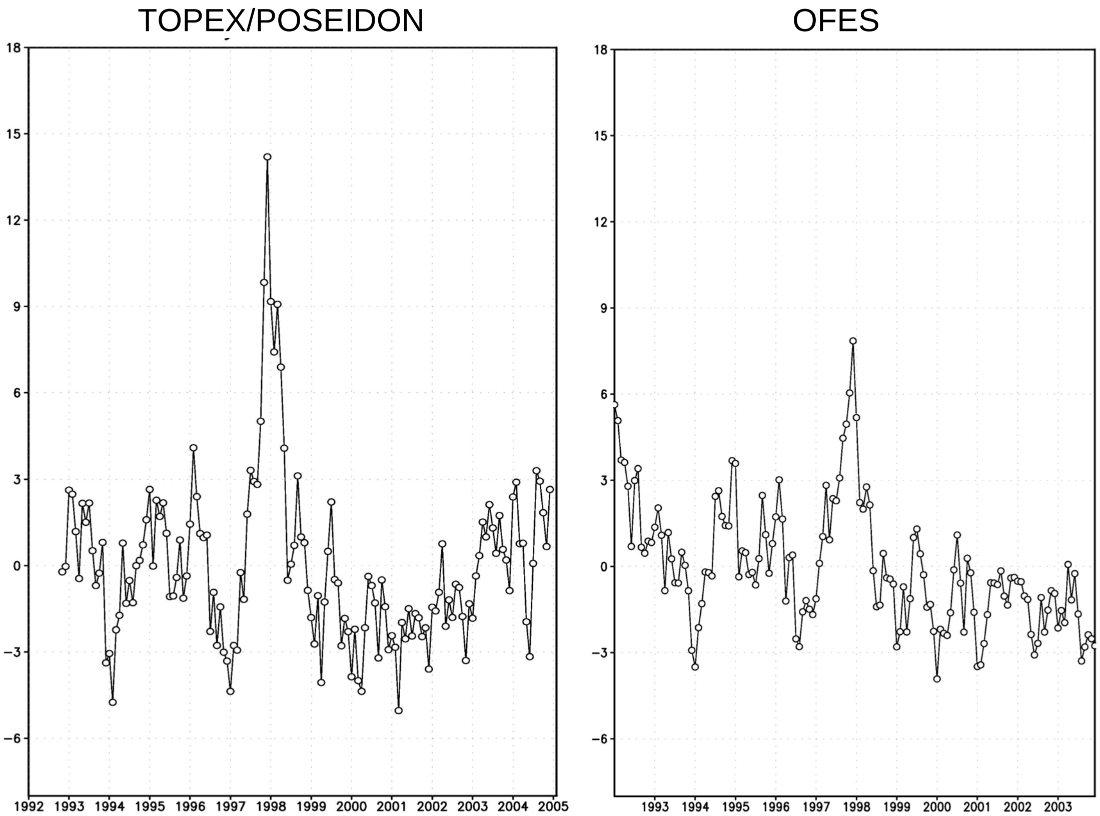

Figure 5. Monthly SSH variance from between the equator and 18^{o}N and from 40^{o}E to 60^{o}E from Topex/Poseidon (left) and the OFES hindcast run (right). Note the extreme low in the spring of 1994 and the extreme high SSH in the spring of 1998. Both extrema are seen in the OFES simulation.

Composites of the year prior to the onset of El Nino years and the El Nino years have been made from T/P and OFES to investigate the ability to model Arabian Sea climate variations. The strength of the Great Whirl is enhanced compared to the year prior to the El Nino onset and compared to climatology, a result in agreement with the model by Jensen (2007). A more detailed analysis is in progress.

Eddy statistics

An important result is that a difference in variance between the climatological OFES run and the hindcast run reveals that 60% of the SSH variance is due to internal variability of the flow. Figure 6 below shows an example of the good agreement for EPE computed for August. The three local maxima in EPE associated with the Great Whirl seen in the observations is simulated well in the hindcast, but is absent in the run forced by monthly climatology. The agreement between OFES and T/P satellite data is typical for monthly maps of EPE, but the best agreement is found during the height of the monsoon seasons.

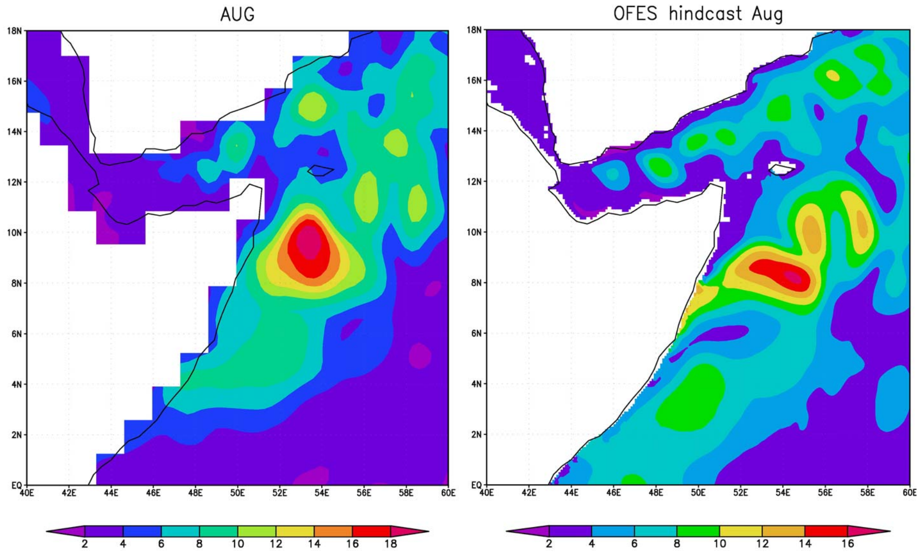

Figure 6. Eddy Potential Energy(EPE) for August.
Overall good agreement between EPE for the Great Whirl and associated eddies is found between the monthly climatology from TOPEX/Poseidon (left) and from the OFES hindcast (right).

Net surface Heat Flux

The WHOI Objectively analyzed sensible and latent heat fluxes (version 3) combined with net long wave radiation and short wave radiation from ISCCP were used to compute a monthly net surface heat flux over the area of interest. An analysis is under way investigating the air-sea interaction over cold core and warm core eddies. It is not clear from the data if a simple relation exists between SST and heat flux over the eddies.

Products

Jensen, T. G.: Evolution of the Somali Current during La Nina, El Nino and Indian Ocean Dipole years. Manuscript in progress.

Jensen, T. G., (2008): Variability of the Somali Current System. Topex/Poseidon and OFES results. Powerpoint presentation.

IMPACT/APPLICATIONS

The Gulf of Aden is important for the world economy. It is one of the most active shipping lanes in the world, connecting the Indian Ocean to the Suez Canal. Over 22,0000 ships pass through the Gulf annually.. Nearly 3 million barrels of oil are transported through the Gulf of Aden daily. In addition, Yemen currently exports 350 to 370,000 barrels per day of crude oil through the terminals at Ras Isa and Ash Shihr. To the south near the island of Socotra and near the Somali coast shipping is exposed to attacks from pirates at an increasingly alarming rate. In 2007 there were 13 attacks. In 2008 there has been at least 61 attacks. It is expected that a better knowledge of the currents, in particular the

seasonal changes of the energetic mesoscale eddies in Gulf of Aden, will be useful for naval ship operations, search and rescue and control of oil spills in this important geographic area.

RELATED PROJECTS

There are no related projects.

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